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# Wave Field Synthesis by Multiple Line Arrays

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**ABSTRACT**

Wave field synthesis (WFS) is a spatial audio rendering technique that produces a physical approximation of wavefronts for virtual sources. Large loudspeaker arrays can simulate a virtual source that exists outside of the listening room. The technique is traditionally limited to the horizontal plane due to the prohibitive cost of planar loudspeaker arrays. Multiple-line-array wave field synthesis is proposed as an extension to linear WFS. This method extends the virtual source space in the vertical direction using a fraction of the number of loudspeakers required for plane arrays. This paper describes a listening test and software environment capable of driving a loudspeaker array according to the proposed extension, as well as the construction of a modular loudspeaker array that can be adapted to multiple-line configurations.

## 1. INTRODUCTION

One principal limitation of wave field synthesis is the restriction of virtual sources to the horizontal plane. It remains impractical to perform wave field synthesis using planar arrays due to the number of loudspeakers involved. To escape limitation to the horizontal plane without a geometric increase in the number of required loudspeakers, we propose a configuration of vertically separated linear arrays to expand spatialization to the vertical axis. It is proposed that this can be achieved without perceptual compromise. We extend existing approximations without introducing new errors into the synthesized wave field, and without introducing unacceptable limitations.

When wave field synthesis is performed with a horizontal line array, the listener receives a physically valid wavefront in the horizontal direction. But the accuracy of this wave field does not hold in the vertical direction. The wave field is only valid on the horizontal plane that contains the entire loudspeaker array. This is an acceptable approximation because acoustic perception is most exact in the horizontal plane, and the listener can be expected to remain in a constant vertical position. With this in mind, we propose that spatialization for elevated virtual sources can be performed with amplitude panning without losing the horizontally stable field characteristics of WFS.

In the proposed model, identical loudspeaker line arrays are placed at low and high positions. Virtual sources are steered with wave field synthesis in the horizontal (azimuth) axis and in depth, and with amplitude panning in the vertical (elevation) axis. For example, if a virtual source is positioned between a line array and another identical line array positioned 2 meters above it, a single horizontal WFS solution is calculated and emitted at equal gain from both top and bottom line arrays. If the virtual source moves closer to the top array, the WFS solution is attenuated in the bottom array and intensified in the top array, just as the phantom source in conventional stereo amplitude panning. Therefore, the virtual source, based on the description of its synthesis method, is now both a phantom source and a virtual source. For discussion purposes, we call this a phantom virtual source. The distinction between phantom sources (produced by stereo amplitude panning), virtual sources (produced by wave field synthesis), and phantom virtual sources (produced by the proposed method) is important. This terminology is used by Wittek [8] and others.

## 2. IMPLEMENTATION

### 2.1. WFS Designer

WFS Designer was developed to perform wave field synthesis in multiple line arrays according to the proposed method. It is an open-source, cross-platform application for performing wave field synthesis with large speaker arrays. In contrast to other wave field synthesis applications that provide a top-down 2D view of the audio scene, WFS Designer allows positioning of virtual sources in a full three-dimensional space.

WFS Designer provides different synthesis modes to address spatial aliasing, including band-limited WFS and sub-band mixing, proposed by Lopez [3]. In the sub-band mixing mode, the high-frequency content is reproduced with amplitude panning. WFS Designer supports several array configurations including line, circle, box, and stacked arrays.

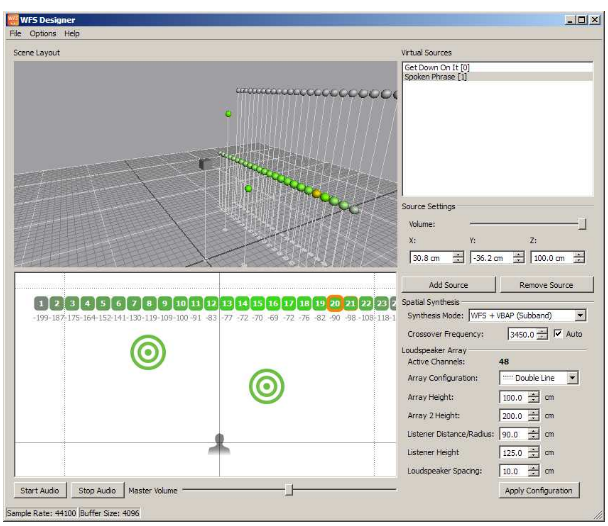


Figure 1: WFS Designer

### 2.2. Modular Array

The speaker array constructed for the research consists of 12 modules of 4 loudspeakers each. The loudspeaker modules are 50 cm by 12.5 cm, with equal loudspeaker spacing, such that each speaker occupies a 12.5 cm square. The modules can be stacked on the short edge or the long edge, and the individual loudspeakers will maintain positions on the 12.5 cm grid. The spatial aliasing frequency arising from this loudspeaker spacing is 2.7 kHz. Above this, the synthesized wave field is not coherent. The loudspeakers are amplified on 48 discrete channels with Sure Electronics TPA3123 stereo amplifier boards. The material cost-per-channel, including amplification, was around $22.

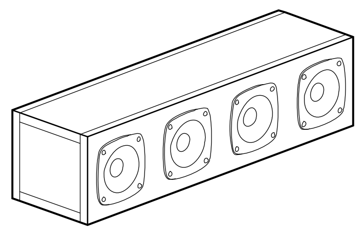

Figure 2: Loudspeaker Module

## 3. LISTENING TEST

A listening test was devised to evaluate the perceptual validity of the phantom virtual source. A loudspeaker array was configured in two 20-loudspeaker rows at a height of 82 and 216 cm. The bottom row was positioned 290 cm away from the listener location. A curtain was placed between the listener and the loudspeaker array to reduce the "ventriloquist effect." The curtain provided a surface for listeners to shine a laser pointer at, indicating the perceived direction of a sound source.

Thirteen subjects participated in the test. Subjects were asked to indicate the perceived direction of test tones by shining a laser on the curtain. Listeners were tested at three different listening positions to validate the stability of the virtual source. The position of the laser on the curtain was photographed for each test tone. In total, 170 test tone evaluations took place in 17 test runs among 13 listeners.

Each test run consisted of 10 tones rendered as spherical sources in the WFS Designer software environment. The test tone consisted of six 0.5 second pulses of white noise. The noise was band-limited to the spatial aliasing frequency of 2.7 kHz. Listeners were able to repeat each test tone upon request. Each of the 10 test tones varied in its virtual source position. The virtual sources were positioned as indicated in Figure 3. These 10 positions were chosen so that 1) the stable source positioning characteristic of traditional wave field synthesis could be validated, and 2) phantom virtual sources could be evaluated independently of virtual sources for analysis and comparison. As shown in Figure 3, test tones 3, 4, 5, and 9 are placed on the extreme upper or lower edge of the valid virtual source space so that they activate only the top or bottom row of loudspeakers. This makes these sources virtual sources as produced by traditional WFS. Test tones 1, 2, 6, 7, 8, and 10 are positioned somewhere between top and bottom so that they are reproduced by both rows, and qualify as phantom virtual sources.

## 4. RESULTS

The reported source positions of all 170 listening trials are superimposed in Figure 4. The reference position is subtracted so that only the localization error remains. The data points are separated into two groups; dashes represent trials for virtual sources, while crosses represent trials for phantom virtual sources.

The overall vertical localization error was higher than the horizontal localization error, with a sample standard deviation of 6.5 degrees. The horizontal error exhibited a standard deviation of 3.3 degrees. It is apparent from Figure 4 that the results of virtual sources are not significantly different from results for phantom virtual sources.

Single factor analysis of variance can be used to test whether two groups of data represent different probability distributions. The test data were grouped into two batches: localization error of all trials with a virtual source, and localization error of all trials with a phantom virtual source. ANOVA was performed on these two groups, and supported the null hypothesis that the localization error does not significantly differ between virtual sources and phantom virtual sources.

## 5. CONCLUSION

The objectives of the research were to build a low-cost, modular loudspeaker array, create an open-source, cross-platform wave field synthesis software environment, and enhance wave field synthesis by expansion to the height dimension. In these respects, the project was successful. The proposed enhancement to WFS was experimentally validated. The modular loudspeaker array will remain at the University of Miami to support future research.

## 6. ACKNOWLEDGEMENTS

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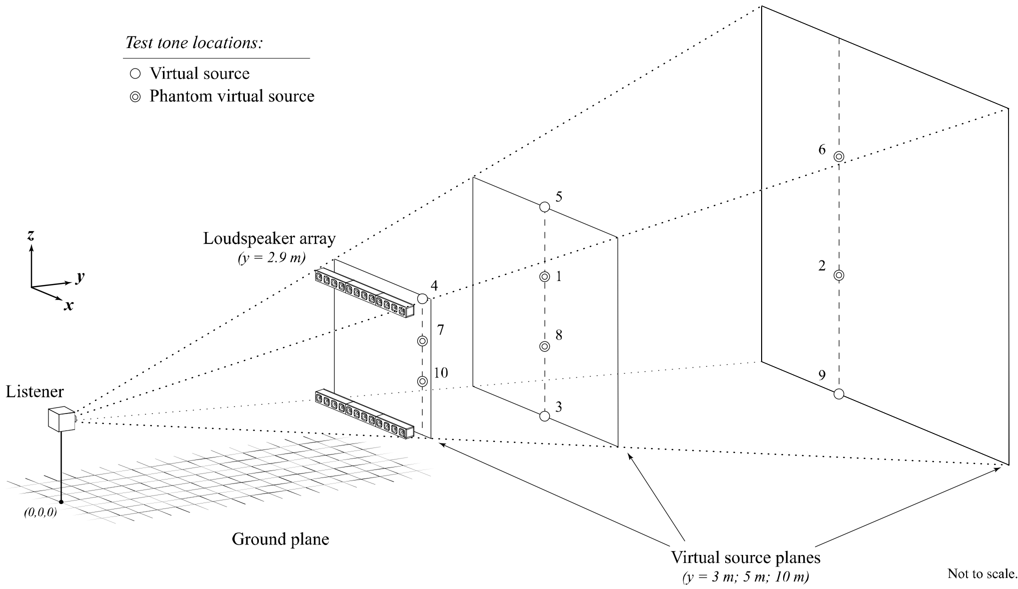


Figure 3: Test tone virtual source locations.

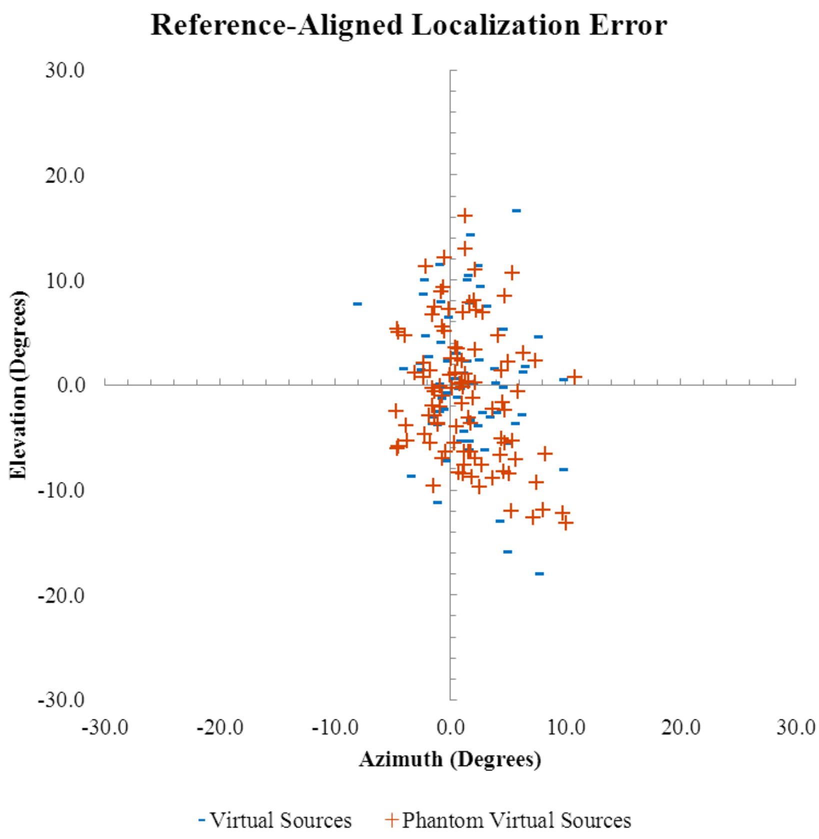


Figure 4: Localization error for all trials grouped by source type.